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THE RESISTANCE OF MATERIALS TO FRACTURE PROPAGATION AND GUNFIRE DAMAGE

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NAVAL RESEARCH LABORATORY
Washington, D.C.

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CONTENTS

ABSTRACT

This report briefly describes the theory and procedures used in the Ballistics Branch, Naval Research Laboratory for determining the toughness of materials.

It is necessary to separate the total work for crack propagation into two terms: (a) the work per unit crack area used in producing permanent set or that at best slowly recoverable, and (b) the work per unit crack area not associated with permanent set. The latter term is presumably a measure of the fracture surface roughness or of the surface area created. This can be much larger than the ideal cross section area broken. The permanent set work is important in that stored elastic energy can thereby be absorbed and self unloading can occur, at least in the case of fixed deflections and in systems capable only of slowly supplying energy from an outside source. The non-permanent set work per unit area is a direct measure of the stress near the crack necessary to keep it progressing. The permanent set work is often highly dependent on the dimensions of the test piece or structure, as well as on the material and temperature. The non-permanent set work per unit area designated $\mathcal{G}_c$ in this report is relatively insensitive to specimen geometry and dimensions and it is therefore more nearly a materials property. It is not completely so, however. It can be shown that $\mathcal{G}_c$ in a given material depends on the roughness of the fracture and this in turn can be temperature dependent. In general it is less temperature dependent than the permanent set work.

By the judicious choice of a probable value of $\mathcal{G}_c$ for a given material it is possible to predict with fair accuracy the strength of a structural

member containing a crack of known or assumed dimensions. Calculations of the strength of a damaged piece have been in good agreement with experiments.

Gunfire damage experiments were performed not to provide design data or to duplicate battle conditions but rather to reveal some of the important factors which must be kept in mind in planning and interpreting such tests. Materials were rated by gunfire tests, but only in a relative sense. Two extremely different kinds of missile were chosen to show that the degree of cracking and tearing can depend on the missile and that the test results are sensitive to this variable. Other test variables are also discussed.

PROBLEM STATUS

This is a report to the Bureau of Aeronautics, Navy Department. Material for the report is drawn from work done of NRL Problem 62F01-03 entitled "Fracture Studies", NRL Problem 62F01-06 entitled "Fracture Resistance of Aircraft Metals" and NRL Problem 62F01-05 entitled "Investigation of Glazing Materials for Aircraft". NRL Problem 62F01-06 was terminated 6 October 1954. Problems 62F01-03 and -05 are continuing. Problems 62F01-05 and -06 received full support from BuAer.

AUTHORIZATION

NRL Problem 62F01-06
Project No. AE-4100

The Resistance of Materials to Fracture Propagation and Gunfire Damage

Introduction

Fracture studies in the Ballistics Branch at Naval Research Laboratory have leaned heavily on the early work of Griffith[1] and the modifications proposed by Irwin[2].

Although Griffith is widely known and followed, it seems appropriate to mention the assumptions that Griffith made. Griffith stated

$$\frac{\partial E_s}{\partial A} \geq \frac{\partial w}{\partial A}$$

as the condition for fracture instability. This assumes that all of the energy for fracturing comes from the store of elastic energy in the test piece. In other words fixed grips are tacitly assumed. The above relation also says nothing about how far the crack will propagate once instability is achieved. This is an important consideration in fail-safe design which require further research. Practically nothing has been written by the well-known fracture experts on the unloading effect. This results from the too commonly made assumption of an infinite test piece.

Secondly, Griffith derived

$$-\frac{\partial E_s}{\partial A} = \frac{\pi \sigma^2 x}{2E}$$

as the energy release rate for an infinite plate containing a through crack of length x. E is Young's modulus and σ is the uniform stress remote from the crack. This expression is independent of the first one and it is based on the assumption of zero permanent set. In general this is not true so we must write for the case of crack propagation

$$\frac{dW}{dA} = F\,\frac{d\ell_p}{dA} + \frac{dG}{dA} \qquad \ldots (1)$$

where dG/dA is the work per unit area not associated with permanent set. This is also referred to as $\mathcal{G}_c$. The rougher the surface the greater is dG/dA in a given material. dG/dA is usually determined to be about 1000 times the theoretical surface energy based on an ideal flat surface representing the cross section of the piece being fractured. dA is an increment of cracked cross sectional area. If permanent set occurs, Griffith's first relation is still correct for fixed grips, but the total energy release rate exceeds that given in Griffith's second relation by an amount not subject to calculation.

This report deals only briefly with the fail-safe concept and with plastic flow. Much remains to be done on these subjects. The report deals with formulae used in computing $\mathcal{G}_c$ for various situations, provides tables of data for various materials and gives data on and a discussion of the load bearing capabilities of aircraft metals subjected to missile damage while under load.

An important concept to be used in this report is that of "$\mathcal{G}$" the driving force per unit length of crack front. When $\mathcal{G} \geq \mathcal{G}_c$ the crack is unstable. This is an exact and more useful expression than the original Griffith expression for instability in that no assumption of fixed grips is involved. The concept of instability here is broadened to include the case of any growing crack regardless of propagation speed or the rate of change thereof.

The Spring Energy Method

It is possible in some cases to determine the driving force $\mathcal{G}$ on a crack by an entirely experimental approach. It must be assumed that a structure or

specimen containing a crack is subjected to a single load F and that the elastic, recoverable component of the deflection δ is given by $F = M\delta$ where M is the spring constant. It is further assumed that locked internal stresses do not form an energy source which assists in the propagation of the crack. Then the spring energy E_s is given by

$$E_s = \frac{1}{2}\frac{F^2}{M}$$

and

$$-\left(\frac{\partial E_s}{\partial A}\right)_{d\ell_p=0,\ \delta=\text{const}} = \frac{1}{2}F^2\frac{\partial(\frac{1}{M})}{\partial A}$$

$d\ell_p = 0$ and δ = const = elastic recoverable deflection. $d\ell_p = 0$ means that the permanent set is not changing. The right hand member is then identified with $\mathcal{G}$, the driving force on the crack. It is important to note that this statement

$$\mathcal{G} = \frac{1}{2}F^2\frac{\partial(\frac{1}{M})}{\partial A} \qquad \ldots (2)$$

is true independent of whether permanent set is actually occurring. That is to say, if the crack extends in area dA, the amount of work done by the force F in extending the crack dA is $1/2\ F^2\ d(1/M)$, exclusive and in addition to work done in producing plastic flow. It is easy to show that $-\frac{\partial E_s}{\partial A}$ is numerically equal to the term dG/dA used in equation (1). It is not assumed that the plastic flow is zero in any of the tests reported here, also none of the working formulae presented here use that assumption. This was illustrated by a simple diagram included as Fig. (1) in ref. 3. A mathematical treatment was included in ref. 4.

In practice the specimen is made to contain a saw cut to simulate the crack. The root radius of the cut is of little consequence insofar as the elastic energy of the system in concerned. Load deflection curves are then

obtained for different length saw cuts and the series of spring constants M_1, M_2, etc. are then obtained. Next, a plot of $1/M$ vs. A or of x = saw cut length is plotted and the slope of the function $1/M$ vs. A or x is measured graphically. This gives a numerical value of $\frac{d(\frac{1}{M})}{dA}$ for any chosen crack length which can be inserted in equation (2). The total derivative $\frac{d(\frac{1}{M})}{dA}$ is now considered equal to $\frac{\partial(\frac{1}{M})}{\partial A}$. This is permissible only for modest amounts of permanent set. If plastic flow changes the spring constant of the piece by an amount comparable with the change resulting from extending the crack, then a calibration of $1/M$ vs. A depending on saw cuts with negligible plastic flow will be in error. This source of possible difficulty has not been encountered in our experiments to date. The technique has been successfully used for measuring the driving force on cracks or slits emanating from openings of various shapes in panels. This procedure was described in detail and used in references 5 and 6. The results showed that a crack starting at an opening such as a door or window is equivalent in danger to a crack as long as the total opening width plus the present crack length. The Lockheed Aircraft Corporation at Burbank, California has verified this result using much larger specimens than those used at NRL. The results are contained in unpublished company reports.

The technique of using changes in the spring constant with increasing crack depth to provide measurements of $\mathcal{G}$ and $\mathcal{G}_c$ for aluminum alloy in slow bend specimens has been used successfully at the University of North Carolina on a contract with NRL. Those unpublished results show that for plate material 2024T4 having side notches, the $\mathcal{G}_c$ is about 200 in.lb/in^2, whereas for sheet 0.030 to 0.040 in. thick, numerous determinations at NRL and elsewhere yield values of around 500 in.lb/in^2 (non-permanent set component).

It should be pointed out that the experimental spring energy method requires the utmost precision in the measurement of the deflections. Although extremely simple in principal, it is not always feasible because of experimental difficulties.

<u>Formulae for $\mathcal{G}$ and $\mathcal{G}_c$ Based on the Theory of Elasticity. Centrally Notched Plates</u>.

The case of a finite plate containing a central crack perpendicular to the applied uniaxial stress has been used extensively at NRL for determining $\mathcal{G}_c$ for various plate and sheet materials. A formula for this purpose was derived in NRL Memo Reports 237 and 372[7,8]. Although in those reports "dW/dA" was used to characterize the material toughness at the onset of sudden fast fracturing it was specified and measured in such a way as to be equivalent to the more precise term $\mathcal{G}_c$ = dG/dA = non-permanent set work per unit area = critical driving force necessary to make the crack advance. The derivation was based on previous theoretical work by Greenspan concerning a finite plate[9]. This formula as used for a centrally notched plate is as follows:

$$\mathcal{G} = \frac{\pi F^2}{BEt^2} \frac{y(2+y^4)}{\left[2-y^2-y^4\right]^2} \qquad \ldots (3)$$

where F = load on the plate or sheet, B = width of plate or sheet, E = Young's modulus, t = plate thickness, y = x/B and x = crack length. The driving force $\mathcal{G}$ exists for all positive values of F and y. If the crack is moving, then $\mathcal{G} = \mathcal{G}_c$. This neglects forces used for particle acceleration. In the investigation of glazing materials the value of $\mathcal{G}_c$ was determined only at the point where the crack propagation speed suddenly changed from slow to very fast. $\mathcal{G}_c$ values characteristic of slow propagation could have been determined at any point prior to this. Most of the values of $\mathcal{G}_c$ shown for

metallic sheet in Table I were determined by using equation (3) for the slow to fast fracture.

Thousands of determinations of $\mathcal{G}_c$, sometimes called dG/dA, have been made for acrylic resins using different crack lengths on a given size specimen, equal crack lengths on different sized plates, and crack lengths scaled with specimen size in all cases keeping thickness constant. The $\mathcal{G}_c$ or dG/dA values for acrylics were found to be independent of crack length for $y \leq 0.5$, and practically independent of specimen size using either scaled or non-scaled crack lengths. It is believed that for scaled crack lengths a small size effect on $\mathcal{G}_c$ may exist but this is apparently very small as compared with individual scatter. In order to reduce the relative standard deviation of the average $\mathcal{G}_c$ to about 10% it is usually necessary to test about 10 specimens. For metals dimensional effects on $\mathcal{G}_c$ have been more severe. See Table I. Calculations of $\mathcal{G}_c$ for mild steel were based on University of Illinois test results for centrally notched plate. The large effect of plate width is shown in Fig. 6. In Fig. 6 it appears that except for plate widths below 12 in. $\mathcal{G}_c$ was proportional to the plate width. This is the same as saying that the average stress on either the gross sections or on the holding section was about the same for all the fractures. All specimens were scaled with respect to crack length at the point for which $\mathcal{G}_c$ was calculated. In the case of aluminum alloys tested at NRL insufficient work has been done to allow one to generalize on the effects of specimen dimensions on $\mathcal{G}_c$. It appears now that no simple rule applies. Present indications are that $\mathcal{G}_c$ may vary by a factor as much as three depending on specimen dimensions but not by as much as a factor of ten.

It is helpful to have automatic wide plate grips for work on centrally notched plates. Several sets of such grips have been designed by M. Brossman and built for this use at NRL. These grips are used for both metals and plastics. The drawings are shown in Figs. 1, 2, 3 and 4. Curved grip inserts (Fig. 5) permit the testing of singly curved specimens to be pulled in the direction of the cylindrical axis of the specimen.

Irwin[10] has utilized a complex Airy stress function provided by Westergaard[11] to calculate the stress system at the tip of a crack and the displacements of the crack boundary for a number of situations. By integrating the displacement times the stress at a properly chosen point beyond the end of the crack the elastic work for a small increment of closure is obtained or for crack extension the work value so obtained is the non-permanent set work expended or $dG/dA = \mathcal{G}_c$. For the case of a centrally notched finite plate of width B, Irwin has derived

$$\mathcal{G} = \frac{\pi \sigma_0^2 x}{2E} \frac{\left(\tan \frac{\pi x}{2B}\right)}{\frac{\pi x}{2B}} \qquad \ldots (4)$$

If the crack is moving $\mathcal{G} = \mathcal{G}_c$. σ_0 is the nominal tensile stress on the gross area remote from the crack.

Edge Cracks - For the edge crack in a plate under tension σ_0

$$\mathcal{G} = \frac{\pi \sigma_0^2 x}{E} \qquad \ldots (5)$$

where x = crack depth.

For an edge crack with a pair of splitting forces P and crack length x

$$\mathcal{G} = \frac{4P^2}{\pi E x} \qquad \ldots (6)$$

A. A. Wells has discussed this relation and its application in considerable detail[12].

Irwin[13] has discussed the case of disk-shaped cracks embedded in massive specimens with tensile stresses normal to the disk and either with or without hydrostatic pressure in the cavity. This case is given by

$$\mathcal{G} = \frac{k(\sigma_0 + p)^2 a}{E} \qquad \ldots (7)$$

where $k = \frac{4(1 - \nu^2)}{\pi}$, a = radius of the disk, p = internal pressure, σ_0 = nominal stress, E = Young's modulus and ν = Poisson's ratio.

A number of other cases have been solved but the foregoing seem to be the ones most likely to be useful for materials evaluation.

Strain Gage Techniques

For cases of plates under tension containing cracks either with or without splitting forces superimposed it is possible to determine the driving force on a crack by measuring the elastic strain in the vicinity of the crack tip. If the crack moves, $\mathcal{G} = \mathcal{G}_c$. For a crack oriented along the x axis a strain gage is placed so as to measure the strain at point r, θ in polar coordinates with the crack tip at the origin and θ the angle between x and r. Irwin has discussed this in ref. 10. If strains ϵ_x and ϵ_y are both measured

$$\sigma_y = \frac{E}{1 - \nu^2}(\epsilon_y + \nu\epsilon_x) \qquad \ldots (8)$$

then

$$\sigma_y = \left(\frac{E\mathcal{G}}{\pi}\right)^{\frac{1}{2}} \frac{\cos\frac{\theta}{2}}{(2r)^{\frac{1}{2}}}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

The use of equation (8) has yielded critical values of $\mathcal{G}$ in good agreement with other methods. Eq. (8) is also useful for showing the crack arresting tendency of stiffeners attached to a panel. If the stiffener is acting as a crack arrester, the value of $\mathcal{G}$ will drop as the crack or saw cut reaches the stiffener while the load is kept constant. It has been noted that for a given value of r, σ is maximum and $\sigma_{max} = \sigma_y$ for $\theta \cong 70^\circ$. This accounts for fracture nucleations or origins ahead of the crack to be off the x axis.

In all of the formulae discussed it may be noticed that the value of $\mathcal{J}_c$ is not the only important materials property in determining the stress for failure. For the purpose of rating a material in every case the failure stress is proportional to $(E.\mathcal{J}_c)^{\frac{1}{2}}$. For materials of greatly different elastic moduli it is necessary to remember this. The reason, of course, is that the greater the value of E the less is the stored energy under a given load and the less is the energy release rate while fracturing. In tabulating the toughness of materials it is therefore recommended that $(E.\mathcal{J}_c)^{\frac{1}{2}}$ be used rather than $\mathcal{J}_c$ (see Table I). If the strength-weight ratio is desired then $\frac{1}{\rho}(E.\mathcal{J}_c)^{\frac{1}{2}}$ should be used as a figure of merit for the material.

Strength and Structural Integrity Under Gunfire

As may be expected military aircraft subjected to battle damage will not be able to operate to the limits of the design performance envelope. The severity of the restriction or the structural kill probability are necessarily greater for brittle materials than for tough materials provided of course that the damage is severe enough. There is no absolute scale by which one material is always better than another. It depends on the extent of the damage. It is not practical to try to inflict "equal damage" by gunfire on panels of widely different aircraft structural metals. The initial crack pattern for a given missile penetration will be greater for one metal than for another. A common factor can be the attacking missile, not the damage it inflicts.

Several previous letter reports to the Bureau of Aeronautics have been prepared on gunfire damage in the Ballistics Branch. Those concerned with metals are listed as refs. 14, 15, 16 and 17. Most of the tests were performed using yawed .50 cal. AP bullets. Materials were rated visually according to the extent of cracking and tearing. Photographic records were provided. A

British report[18] provides similar information, plus a small amount of work on determining limiting stresses for panels subjected to gunfire.

Gunfire experiments were conducted with three purposes in mind: (1) to show up strain energy effects, (2) to show effects of different missiles, i.e. clean punching vs. tearing and (3) to show effects of ratio of hole size to specimen size. It should be emphasized that no attempt has been made to duplicate field or battle conditions. Two missiles were chosen to represent two extremes of behavior. First, a cylindrical steel slug striking end-on served to make a fairly clean punched hole in the target. Cracking or tearing was intentionally minimized. Second, a lead bullet was chosen which produced rather severe tearing and petalling around the hole. It is hoped that the results of the tests will be viewed in the light of these differences rather than as an attempt to simulate real fragments. It is hoped that any evaluation of full-scale structures by more realistic fragment impacts can more easily be planned and interpreted, if the results of this report are kept in mind.

The specimens were placed in a testing machine; the load was stabilized, and the shot was then fired. Table II shows results using a punching type of missile on short specimens. The limiting initial stress is not significantly higher for 24ST3 than for 75ST6. The old alloy designations are used because at the time the tests were made the old system was in effect. Tables III and IV show the effects of lengthening the specimen so as to add to the strain energy reserve in the specimen. The effect is to reduce the amount of unloading which occurs immediately after penetration. The data show that 24ST3 is at increasing disadvantage as the available energy and energy release rate increase. The specimens of Tables II, III and IV were all 6 inches wide and the perforation diameter was close to 0.5 inch in all cases.

The effect of increasing the "severity" of damage by increasing the ratio of missile diameter to specimen width is shown by comparing Tables II and IV. This increase in "severity" was done by retaining the .50 cal. steel slug and decreasing the specimen width to 2 in. As the "severity" of damage is increased the advantage of the tougher 24ST3 becomes more apparent. The values shown for limiting stress are significant only for comparison purposes. It should be recognized that these numbers cannot be used for design calculations. The use of a punching type of projectile does not reveal a spectacular difference in materials but instead tends to show that they are about the same for this kind of attack.

Tearing and cracking during penetration produces an entirely different kind of materials comparison than does the punching. Table VI for 2 in. wide specimens shows the results of penetration by .22 cal. lead bullets. This kind of missile produced severe petalling and cracking in the XA78ST6 and 75ST6, and less severe cracking in the 24ST3. The limiting stress was almost three times as high for 24ST3 as for XA78ST6 and over twice as high in 24ST3 as for 75ST6. Realistic fragments would probably produce losses in strength intermediate between those shown in Table VI and in Table V.

The extreme advantage displayed by 24ST3 in Table VI is somewhat tempered when the store of elastic energy is increased. Table VII shows results similar to those of Table VI, except that the specimens are now 12 in. long instead of 6 in. long. The limiting stress in 24ST3 for the .22 cal. soft bullet attack is appreciably less in the long specimens than in the short ones. This is presumably because the load is maintained higher during the test. With increased severity of cracking and tearing the scatter in results also increases as is evidenced by the mixed results. Any attempt to evaluate limiting stresses or gunfire damage on full-sized structures under load is likely to become expensive, if the scatter is to be adequately studied.

It is apparent that large differences due to materials differences may exist in the ability of airplanes to retain their structural integrity after battle damage. The fail-safe design assumes that cracks will start but that they can be stopped. This is, of course, a relative matter. There is no such thing as an absolutely fail-safe structure. Stopping the crack by virtue of materials toughness and by limiting the supply of strain energy, or more precisely its release rate, through design is only possible if the damage is sufficiently small. There must exist a degree of damage so slight that 24ST offers no advantage over more brittle alloys. This report can only serve as an introduction to the problem of determining the strength of variously constructed aircraft as affected by battle damage.

Conclusions and Suggestions for Further Investigation

1. It is evident that different types of missile will rate aircraft structural materials differently, sometimes in different order with respect to load bearing capability while under attack. Relatively clean punching with restricted cracking by a cylindrical missile scarcely separated the three aluminum alloys tested, on the other hand, a soft deforming missile produced extreme losses in strength of the more brittle alloy specimen, but relatively minor losses in the strength of 2024T4 specimens. It is suggested that similar measurements should be made using realistic fragment simulators. The 90° yawed cylindrical dart with conical ends is considered a realistic fragment simulator for research purposes in the Ballistics Branch. If the statistical scatter in realistic fragments and their effects is to be studied then perhaps rectangular parallelepipeds tumbled at random should be used. Such fragment simulators and rectangular bore guns are available at NRL.

The effect of striking velocity on the amount of plastic bulging around the hole in thin metal plates has been studied at NRL by Clark[19,20] and Krafft[20]. Sharp edged parallelepipeds as fragment simulators have been investigated at NRL by Clark[21].

2. The load bearing capabilities of specimens fired while under stress may or may not be less than that for specimens fired while under no load and then tested for strength. If the missile imposes transient stresses which are sufficiently large and apply for a sufficient time there will be a difference, of course. This problem needs more investigation.

3. The ability of a metal to deform plastically and, thereby, reduce the stresses in the vicinity of a crack has not been investigated in a quantitative fashion. To do this a testing machine of great rigidity is needed, preferably one with a mechanical drive. NRL has a new 3,000,000 lb. machine designed for this purpose. The load should be applied and the deflection of the specimen fixed as nearly constant as possible. The drop off in load as a result of missile penetration would be from two distinguishable and measurable causes, (a) loss in elastic rigidity or spring constant due to the hole and cracks, and (b) the plastic extension. It is not known how well ordinary or standard ductility values for materials can be used to predict the self unloading and, hence, crack arresting qualities. For structural applications in aircraft where redundancy may be negligible and constant load, rather than constant deflection, is the service condition, then the capacity for permanent set would be of slight, if any, advantage, whereas the non-permanent set work $\mathcal{G}_c$ for fracturing would be a controlling materials property.

4. A number of formulae and several procedures for measuring $\mathcal{G}$ the driving force on a crack and $\mathcal{G}_c$ the critical value for a material have been presented here. A great deal of experience has been gathered in their use on other problems in the Mechanics Division. The application of these formulae and

procedures to the assessment of the susceptibility of materials to missile damage has not been done. One possible way to accomplish this would be to express the results of various missile attacks in terms of equivalent crack lengths, assuming suitable values of $\mathcal{G}_c$ for the material. $\mathcal{G}_c$ may be dependent on crack velocity. It seems certain that any factor or variable that influences the roughness or complexity of the fracture will have an important effect on $\mathcal{G}_c$.

5. For panels of aircraft metals the measured values of $\mathcal{G}_c$ were found to be somewhat dependent on specimen dimensions. This complication has not been found or at least had proved negligible in thousands of tests of transparent plastics. Dimensional effects in the fracturing of metals need much more study. The University of Illinois central notched tests showed a tremendous effect of dimensions on $\mathcal{G}_c$.[22] This effect is poorly understood and the case serves to illustrate that great caution is required in utilizing results of simple small scale tests to predict th behavior of large structures.

6. It is apparent that large scale tests, i.e. of panels up to four or five feet wide, are needed in a program to evaluate the susceptibility of structural materials to missile damage. It has been pointed out that such tests are likely to be much more expensive than the kinds of test done on this investigation.

7. In other reports, including the British as well as NRL reports, the terms shatter and liability to shatter have been used. A more precise definition of this quality is needed than now exists. The creation of multiplicity of fractures and of forking or branching is known to depend on the stress level, dimensions of the test piece (as they effect enery release rates and extent of unloading) and on the effective $\mathcal{G}_c$. None of these factors has been adequately investigated. Studies of such effects are being conducted on

Research Navy funds in the Mechanics Division.

8. It is suggested that $\sqrt{E.\mathcal{G}_c}$ and $\frac{1}{\rho}\sqrt{E.\mathcal{G}_c}$ be used as figures of merit for the fracture resistance of materials under tension. E is Young's modulus and ρ is the density. It should be emphasized that a high elastic modulus is advantageous for increasing the allowed working stress.

Acknowledgements

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TABLE I

Material	$\mathcal{G}_c$ in.lb/in^2	$E.\mathcal{G}_c$ lb/in$^{3/2}$	Specimen Description (All Centrally Notched Sheets or Plates) Length, Width and Thick. in.	Temp.
75ST6	600 ± 30	79 x 10^3	7 x 7 x 0.041	RT
"	400 ± 30	65	7 x 3½ x 0.041	RT
"	300 ± 10	56	3½ x 1-3/4 x 0.041	RT
"	300 ± 30	56	1-3/4 x 1-3/4 x 0.041	RT
"	600 ± 50	79	3½ x 3½ x 0.041	RT
"	550 ± 10	76	14 x 7 x 0.041	RT
* "	325 ± 50	58	36 x 6 x 0.032	RT
* "	340 ± 50	59	18 x 6 x 0.032	RT
* "	390 ± 50	64	6 x 6 x 0.032	RT
Av. =	350 ± 50	60		
* XA78ST6	255 ± 20	52	36 x 6 x 0.032	RT
* "	282 ± 10	54	18 x 6 x 0.032	RT
* "	300 ± 20	56		
Av. =	280 ± 20	54		
* 24ST3	420 ± 20	66	36 x 6 x 0.032	RT
* "	520 ± 20	74	18 x 6 x 0.032	RT
* 24ST ANRA	420 ± 20	66	6 x 6 x 0.032	RT
7075ST6	320 ± 10	58	6 x 6 x 0.125 Crack parallel to rolling direction	RT
"	460 ± 10	69	6 x 6 x 0.125 Crack perpendicular to rolling direction	RT
"	370 ± 10	62	6 x 6 x 0.040 Crack parallel to rolling direction	RT
"	460 ± 10	69	6 x 6 x 0.040 Crack perpendicular to rolling direction	RT
** Ship Steel	100	55	6ft. x 1 ft. x 1 in.	Below TT
"	1000	173	18 ft. x 6 ft. x 1 in.	" "
MIL P 5425A,B Acrylic Plate	4.5 ± 0.5	1.3	6 x 6 x ¼	RT
MIL P 5425A,B Hot Worked	25 to 40	3.1 to 3.9	6 x 6 x ¼	RT
Cast CR-39	1	0.6	6 x 6 x 1/8	RT
Brit. Ship Steel	74	47	6 x 6 x ½	- 38°F
*** "	86	51	6 x 6 x ½	- 12°
"	153	68	6 x 6 x ½	+ 15°

TABLE I (Cont'd)

Material	$\mathcal{G}_c$ in.lb/in^2	$E.\mathcal{G}_c$ lb/in$^{3/2}$	Specimen Description (All Centrally Notched Sheets or Plates) Length, Width and Thick. in.	Temp.
Tit. RC-130A Annealed (dW/dA = 20,000 in.lb/in^2)	300 ± 20	77 x 10^3		RT
Nylon	17	2.6	6 x 2¼ x 0.011	RT
Cellulose Acetate	32	3.1	6 x 2¼ x 0.0056	RT
**** STS (dW/dA = 22,000 in.lb/in^2)	360	104	10 x 10 x 1	RT

(Each value is the average of 6 to 10 measurements)

*Same material used for gunfire damage studies.
**Calculated from Univ. of Ill. results.
***Calculated from results of T. S. Robertson.
****Tear test in NRL 3,000,000 lb. testing machine.

Gunfire Tests of Stressed Sheets - 0.50 cal. Hollow Steel Slug at Normal Incidence 2000 ft/sec.

TABLE II

6 in. x 6 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	55,000	H	
"	60,000	H	
"	63,000	H	
"	64,000	H	64,500
"	64,500	H	
"	65,000	B	
"	65,500	B	
"	66,000	B	
XA78ST6	59,000	H	
"	59,500	B	
"	60,000	H	
"	60,500	B	59,000
"	61,000	B	
"	63,000	B	
"	65,000	B	
24ST3	60,000	H	
"	65,000	H	65,000
"	66,000	H - Slow B	
"	66,000	H - Slow B	

H = held, B = broke

TABLE III

18 in. x 6 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	60,000	H	
"	62,000	B	
"	62,500	H	62,500
"	63,000	B	
"	65,000	H	
"	65,000	B	
XA78ST6	60,000	H	
"	61,500	H	
"	62,000	H	62,000
"	62,500	B	
"	63,000	B	
24ST3	60,000	H	
"	62,000	H	
"	62,500	B	62,000
"	63,000	B	
"	65,000	B	

Gunfire Tests of Stressed Sheets - 0.50 cal. Hollow Steel Slug at Normal Incidence 2000 ft/sec.

TABLE IV

36 in. x 6 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	60,000	H	
"	63,000	H	
"	65,000	H	71,000
"	67,000	H	
"	70,000	H - B	
"	73,000	B	
XA78ST6	60,000	H	
"	63,000	H	
"	65,000	H	65,000
"	65,500	B	
"	66,000	B	
"	67,000	B	
24ST3	55,000	H	
"	56,000	H	
"	56,500	H	56,000
"	57,000	B	
"	58,000	B	

H = held, B = broke

TABLE V

6 in. x 2 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	55,000	H	
"	57,000	H	
"	57,500	H	58,000
"	58,000	B	
"	58,000	H	
"	60,000	B	
XA78ST6	55,000	H	
"	57,500	H	
"	58,000	B	
"	58,000	H	58,000
"	58,500	B	
"	59,000	B	
"	60,000	B	
24ST3	55,000	H	
"	60,000	H	
"	61,000	H	61,500
"	61,500	H	
"	62,000	B	

Gunfire Tests of Stressed Sheets
0.22 cal. Lead Bullet 1000 ft/sec.

TABLE VI

6 in. x 2 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	20,000	H	
"	21,000	H	
"	21,500	H	
"	22,000	H	
"	24,000	H	
"	24,500	B	
"	25,000	B	24,000
"	25,000	B	
"	30,000	B	
"	38,000	B	
"	40,000	B	
"	45,000	B	
"	48,000	B	
"	50,000	B	
"	53,000	B	
XA78ST6	10,000	H	
"	12,000	H	
"	14,000	H	
"	14,500	H	15,000
"	15,500	B	
"	20,000	B	
"	25,000	B	
24ST3	50,000	H	
"	53,000	H	
"	54,000	H	56,500*
"	56,000	H	
"	56,500	H	
"	57,000	B	

H = held, B = broke

*Note high superiority of 24ST3.

Gunfire Tests of Stressed Sheets
0.22 cal. Lead Bullet 1000 ft/sec.

TABLE VII

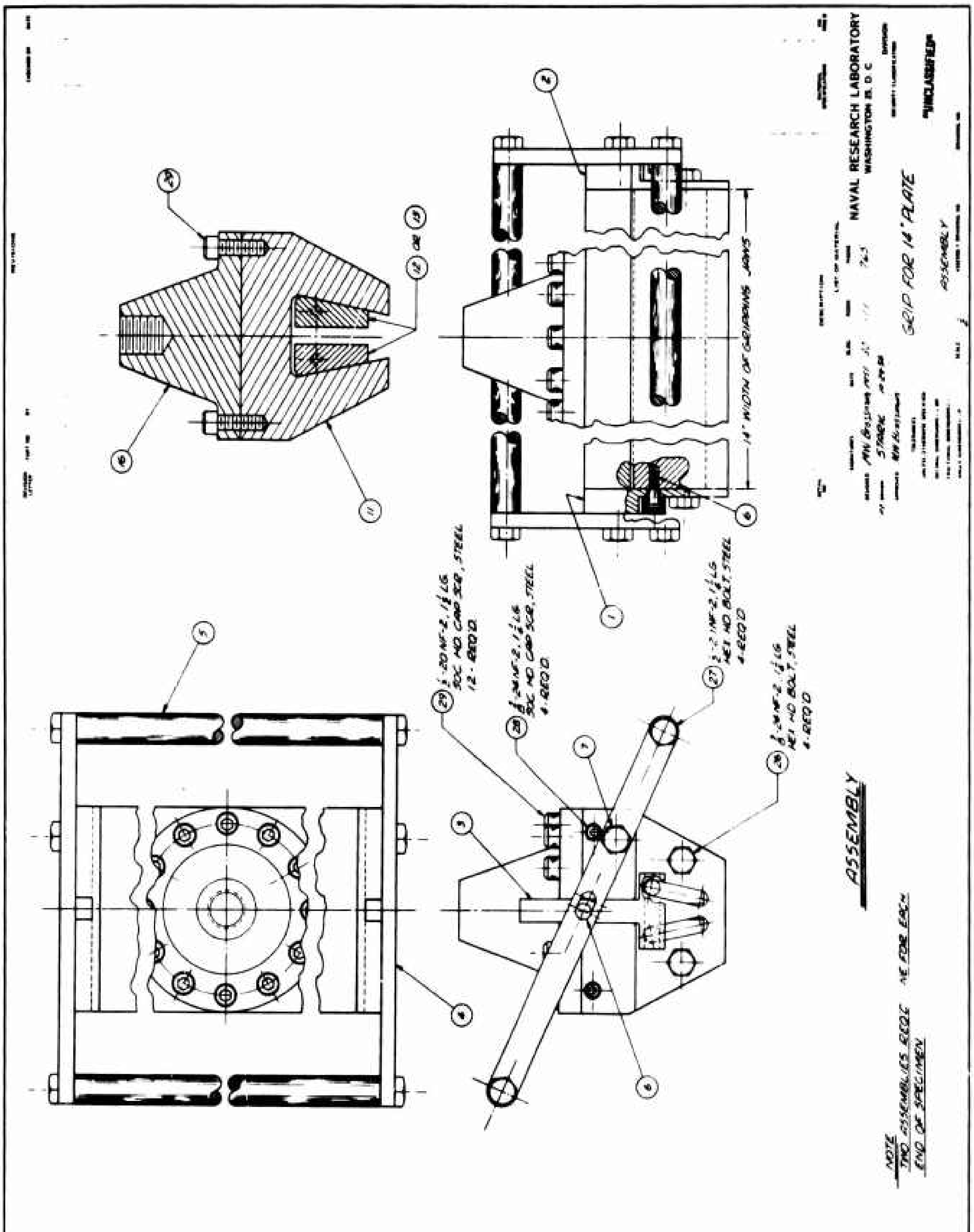
12 in. x 2 in. x 0.032 in.

Material	Stress psi	Result	Limiting Stress psi
75ST6	23,000	H	
"	23,500	H	
"	23,500	H	
"	23,750	B	24,000
"	23,750	H	
"	24,000	B	
"	24,000	H	
"	24,250	B	
"	24,500	B	
XA78ST6	14,500	H	
"	15,600	H	
"	16,000	H	
"	16,500	B	
"	16.500	H	
"	16,750	B	
"	17,000	H	
"	17,000	H	
"	17,250	B	20,000
"	17,500	H	
"	18,000	H	
"	18,500	B	
"	18,500	H	
"	19,000	H	
"	20,000	H	
"	20,000	H	
"	20,500	B	
"	21,000	B	
"	23,000	B	
"	25,000	B	
24ST3	24,000	H	
"	30,000	H	
"	40,000	H	
"	45,000	H	
"	46,000	B	
"	46,000	H	48,000*
"	47,000	B	
"	47,000	H	
"	47,500	H	
"	48,000	H	
"	48,500	B	
"	48,500	B	

H = held, B = broke

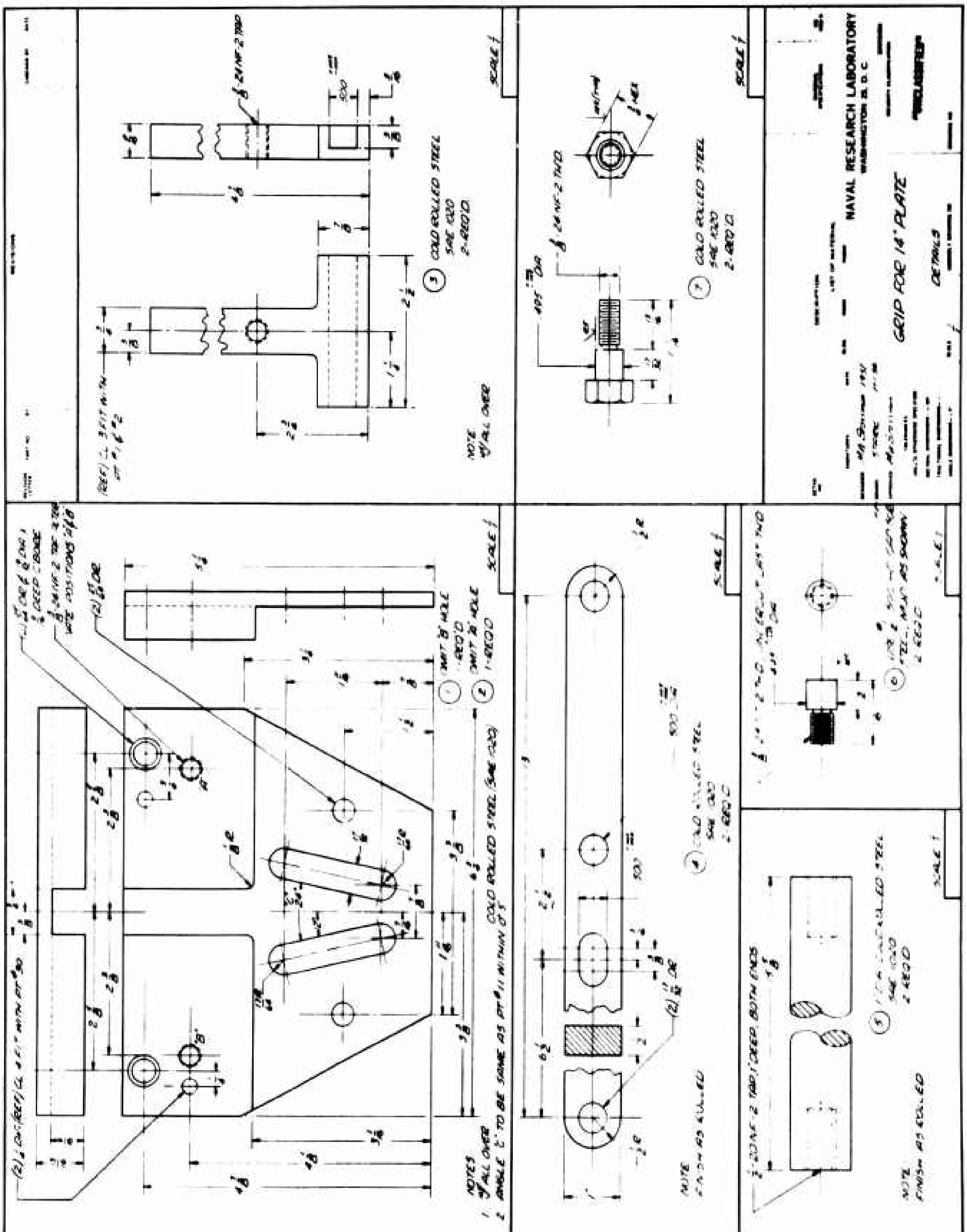
*Note high superiority of 24ST3.

Navy - NRL, Bellevue, D. C.



ASSEMBLY
14" WIDTH OF GRIPPING JAWS
NOTE
TWO ASSEMBLIES REQ'D ONE FOR EACH END OF SPECIMEN
NAVAL RESEARCH LABORATORY
WASHINGTON 25, D. C.
GRIP FOR 14" PLATE
ASSEMBLY
UNCLASSIFIED

Figure 1



NAVAL RESEARCH LABORATORY
WASHINGTON 25, D. C.
GRIP FOR 1/4" PLATE
DETAILS
COLD ROLLED STEEL
SAE 1020
2-REQ'D

Figure 2

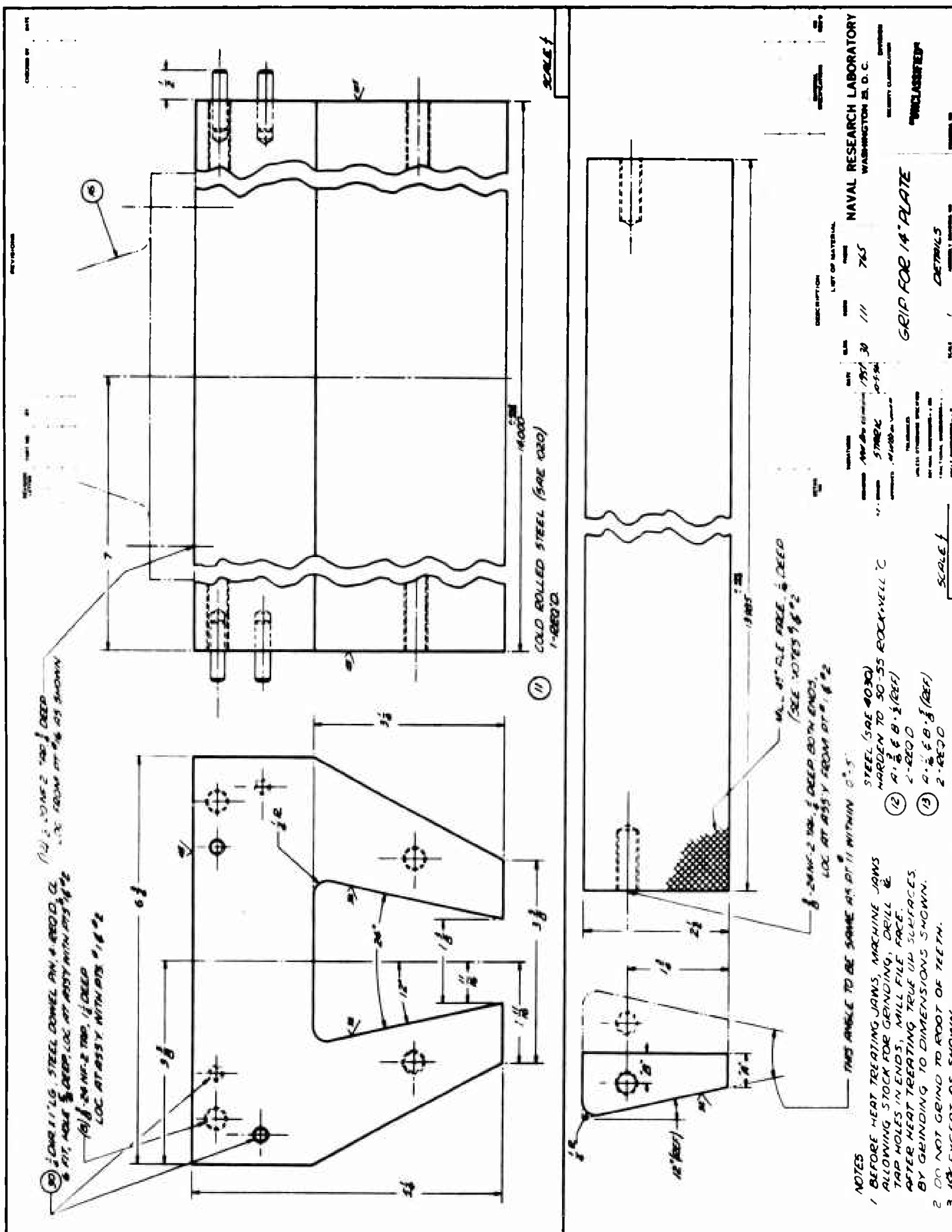

COLD ROLLED STEEL (SAE 1020)
NOTES
1 BEFORE HEAT TREATING JAWS, MACHINE JAWS ALLOWING STOCK FOR GRINDING, DRILL & TAP HOLES IN ENDS, MILL FILE FACE. AFTER HEAT TREATING TRUE UP SURFACES BY GRINDING TO DIMENSIONS SHOWN.
2 DO NOT GRIND TO ROOT OF TEETH.
NAVAL RESEARCH LABORATORY
WASHINGTON 25, D. C.
GRIP FOR 1/4" PLATE
DETAILS

Figure 3

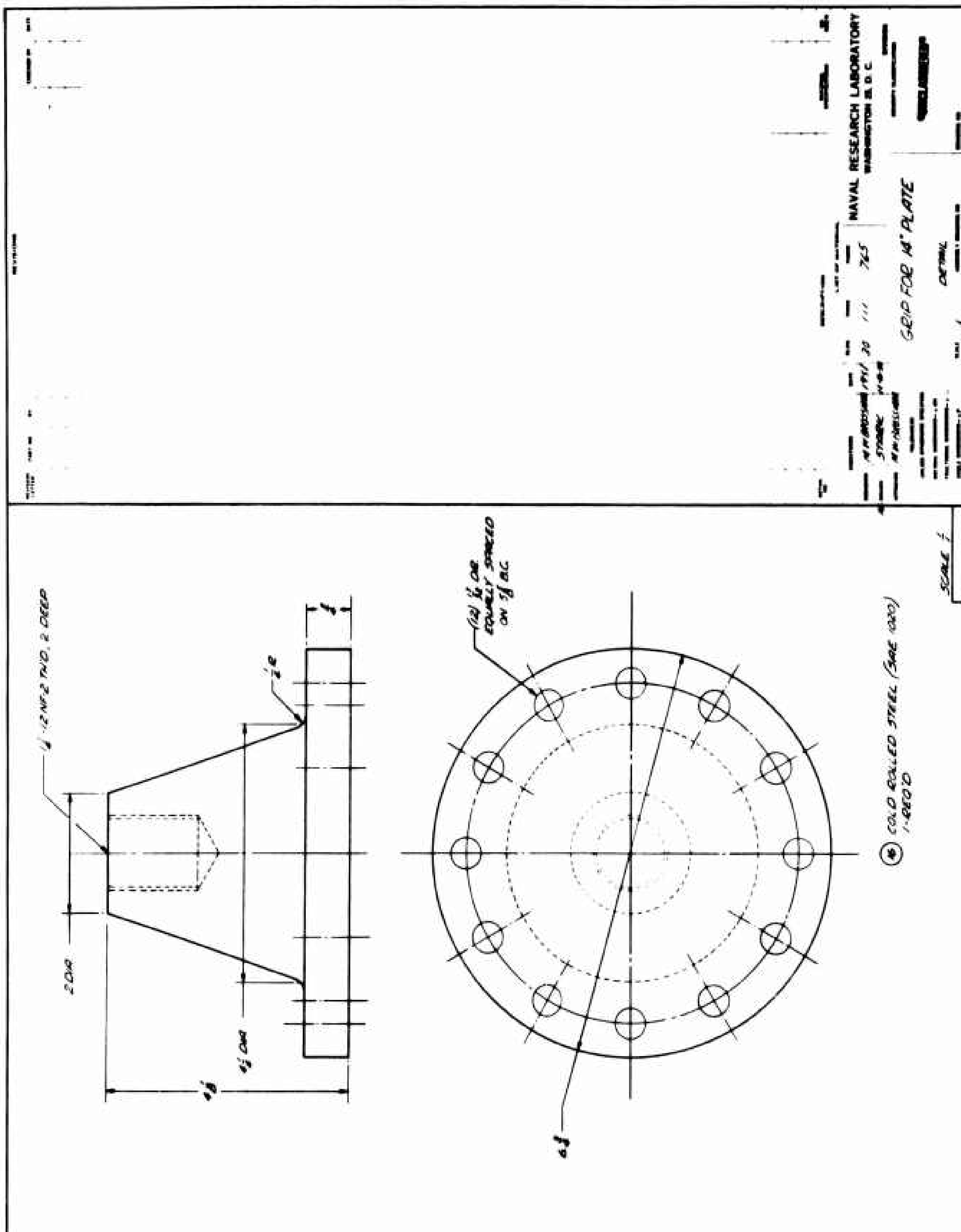

NAVAL RESEARCH LABORATORY
WASHINGTON 25, D. C.
GRIP FOR 14" PLATE
DETAIL
COLD ROLLED STEEL (SAE 1020)
1-REQ'D
2 DIA

Figure 4

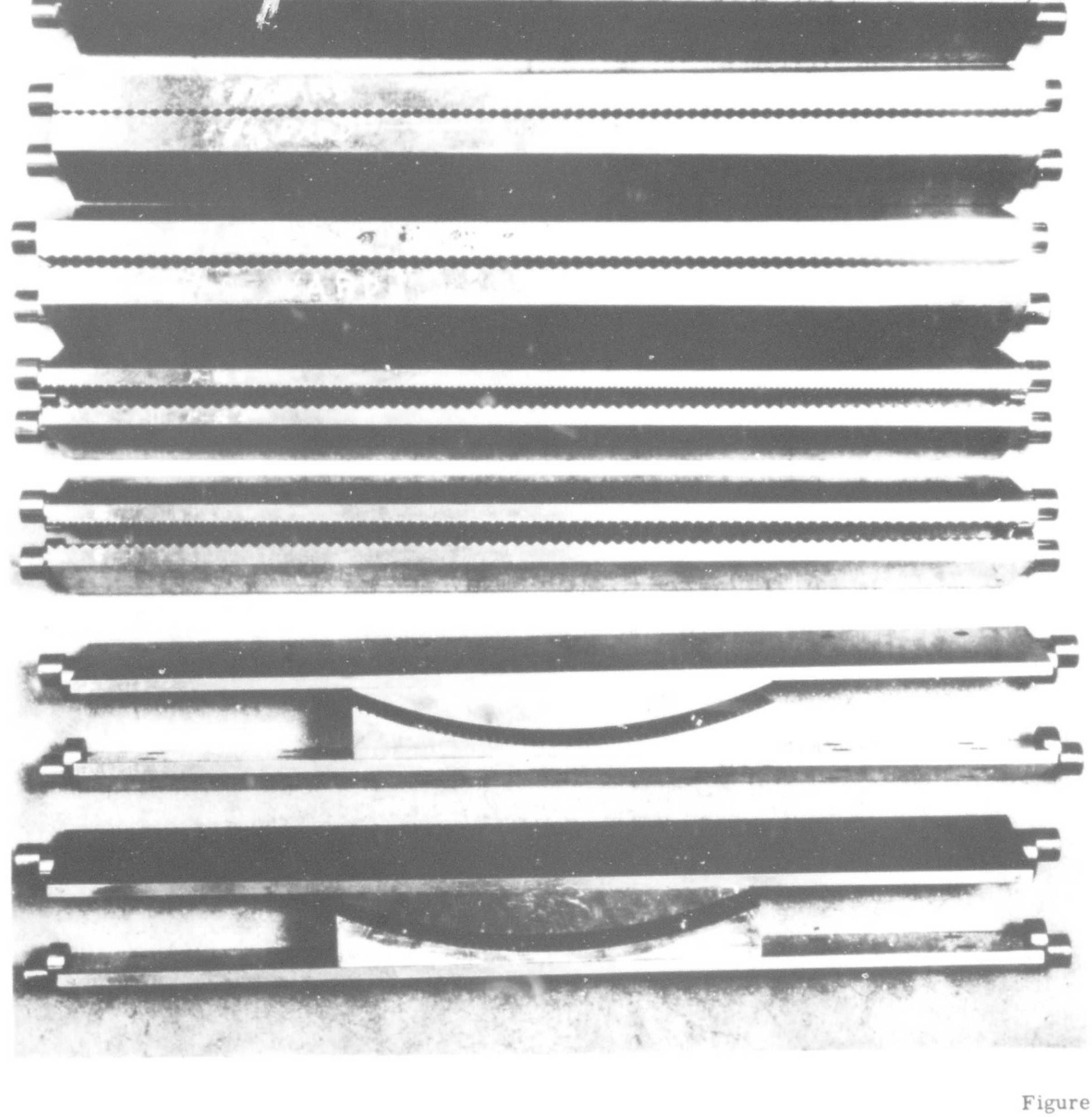


Figure 5

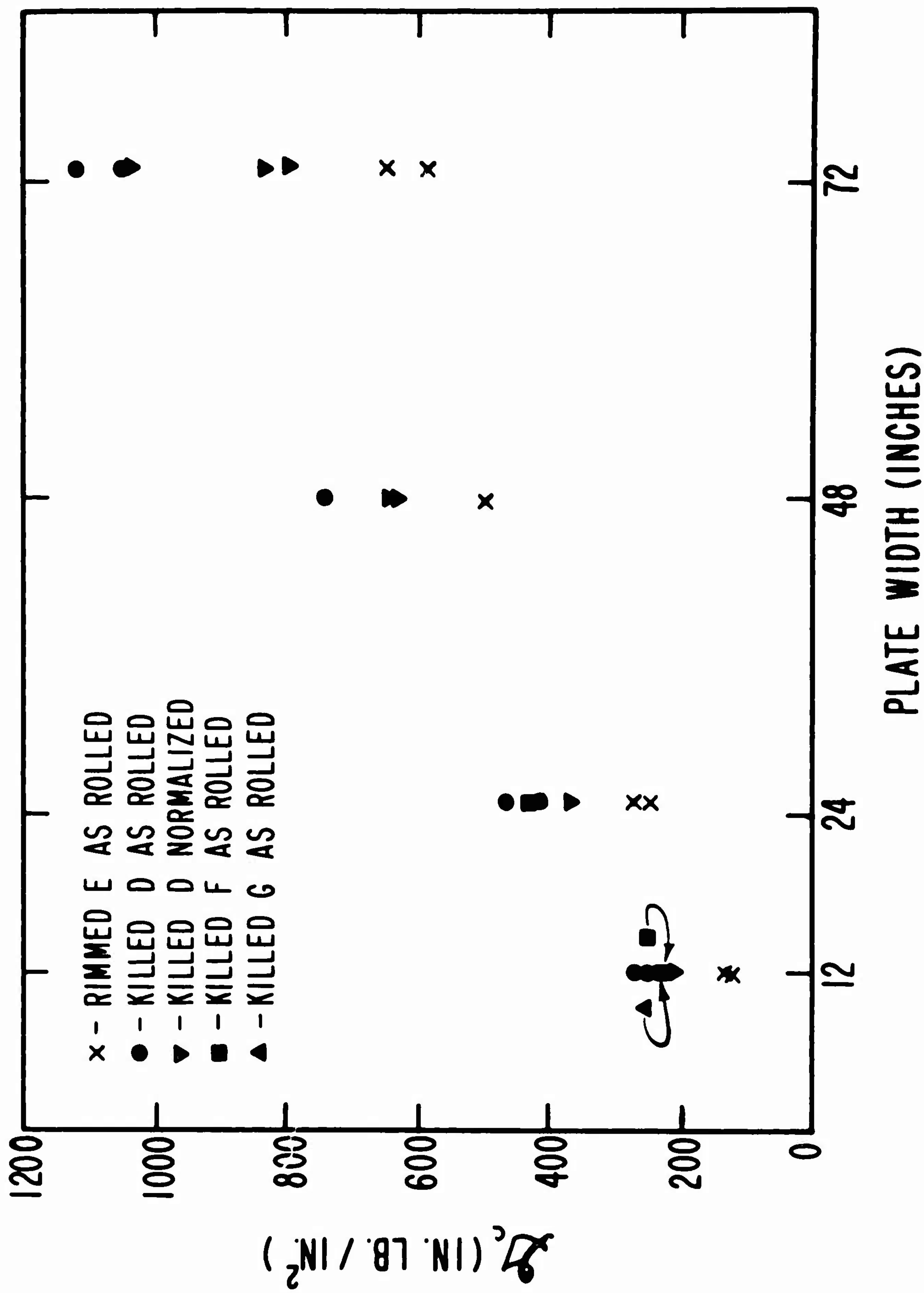

× - RIMMED E AS ROLLED
● - KILLED D AS ROLLED
▼ - KILLED D NORMALIZED
■ - KILLED F AS ROLLED
▲ - KILLED G AS ROLLED
1200
1000
800
600
400
200
0
12
24
48
72
PLATE WIDTH (INCHES)
(IN. LB. / IN.²)

Figure 6